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PM collection performance of electret filters electrospun with different dielectric materials-a numerical modeling and experimental study

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ABSTRACT

Electrospun electret filter has been regarded as a promising medium to remove particulate matter (PM) from air stream because it could fulfill the requirements for both high filtration efficiencies and low pressure drops. The physico-chemical characteristics of the polymer material have significant effects on the PM collection performance of the electret filter. In this study, polyvinyl chloride (PVC), polyacrylonitrile (PAN), polycarbonate (PC) and polyethyleneimine (PEI) electret filters with similar structures are electrospun using polymers of different permittivity and their collection efficiencies for neutral particles are evaluated experimentally. Then the lattice Boltzmann coupled with discrete element method (DEM) is applied to simulate the particle transport and deposition through the virtual 3-D electret filters, to give further insight into the particle capture mechanisms due to the PM-fiber interaction and the dielectrophoretic attraction. The simulation results compare favorably with the experimental data. Results indicate that the PM collection efficiency of PVC electret filter is the highest, and followed by the PAN, PC and PEI electret filters. It is revealed that the dielectric property of the polymer material is an influential factor shaping the interaction of particles and fiber surfaces, as well as the charge storage abilities of the electrospun electret filters. A higher polymer permittivity would lead to a larger PM-fiber adhesion energy, a larger fiber charge density and then a better PM collection performance.

1. Introduction

The particulate matter (PM) pollution in air, especially the $PM_{2.5}$ and its attached biological matter involving bacteria and viruses, have caused a serious threat to people's living quality, climate and ecosystems [1]. Fibrous filters have become a feasible and efficient medium to remove particles from the air stream due to their reticular support structures and tortuous pore channels, which allow the effective passage of air molecules while trapping the particles [2]. However, conventional fibrous filters based only on mechanical filtration mechanism are difficult to meet the simultaneous requirements of high-efficiencies and energy-saving due to their compacted stacking structures [3].

Polymer electret is known for its ability to retain quasi-permanent abundant charges and create an external macroscopic electric field on the periphery of fibers [4]. It could enhance the filtration efficiency without increasing the pressure drop, as a result of the additional electrostatic caption effect. Conventional electret filters, such as PP, have been widely used for building ventilation filtering and personal mask. However, some drawbacks still remain: (1) a microscale fiber diameter and comparatively large aperture size, leading to an extremely low mechanical filtration efficiency (~30%) and high airflow resistance [5]; (2) many layers of thick fibers, resulting in large basis weight and thickness [6].

Electrospinning is one of the most promising methods of creating nanoscale fibers. Profiting from its nanoscale diameter, high tortuous porous structure, and high specific surface area, improved mechanical filtration efficiency and reposeful pressure drop can be achieved for electrospun filters [5,7]. Meanwhile it gives the possibility to form nanofibers electrostatically charged during the fabrication process by charging the polymer solution with an external electrostatic field [8]. Besides, it is easy to incorporate other components into electrospinning solution to develop multifunctional air filters. Recently, several electrospun filters with superior filtration efficiency, obviously low pressure drops and low basis weight compared with typical commercial mechanical/electret filters have been reported [5,9–12].

But it must also be admitted that, the low charge amounts embedded into the electrospun electret filter and fast charge decay due to its low basis weight (mass) remain a problem. Several efforts have been made to further improve the charge storage stability and PM collection performance of electrospun electret filters, through electrospinning

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parameters control [5,13] and inorganic electret addition [14,15]. The dielectric property of the fibers in the filter plays important roles in determining the charge density, hence the filtration performance. Liu et al. demonstrated that a high dipole moment was helpful for capturing ultrafine particles. Nanofiber filter based on polyacrylonitrile (PAN) had the highest dipole moment and it eliminated the $PM_{2.5}$ better than polyvinylpyrrolidone (PVP), polystyrene (PS), polyvinyl alcohol (PVA) and polypropylene (PP) filters [6]. Li et al. also pointed out that the collection efficiency of electrospun polycarbonate (PC) membrane was higher than PVA and PS membranes with similar fibrous morphologies [16]. It is indicated that the polymer polarity is the vital factor impacting the PM-fiber interaction. Lovera et al. found that a blend of polyphenylene (PPE) and PS was observed to give increased charge stability. It was mainly due to the presence of charge trap zone created between the blending boundary, and the dipoles orientating formed in the PPE phase during electrospinning process [17]. Therefore, the behaviors of the electret filters in terms of their charge storage ability and filtration efficiency were found to vary with the constituting fiber materials.

Further insights into this phenomenon are needed to guide the development of better electret filters. These insights can be gained through appropriate modeling of the particle transport and deposition process through an electret filter in a coupled field of electrostatics and viscos flow. However, little research has been conducted on it, especially on the effect of polymer material property. The discrete element method (DEM) follows Newton's second law to calculate the individual element's motion. It could consider the electrostatic, fluid and adhesive contact forces on individual particles. More recently, particle interactions have also been included for fine particulate systems on the micrometer scale [18]. Dong et al. especially worked on the cake build-up mechanisms in filtration and sedimentation process. They could demonstrate the influences of material properties on the cake structure and the contact force network inside the filter cake or sediment [19].

In this study, the influence of polymer dielectric property on the filtration performance of electrospun electret filter, which is a newly-developed and promising filter media is experimentally and numerically investigated. A set of electret filters with similar physical characteristics, such as the filter morphology, the fiber packing density and the average fiber diameter, are electrospun by four different polymer materials. Four mechanical filters are also fabricated by removing the charges from the corresponding electret filters. The variations of their PM collection efficiencies for neutral particles with the dielectric materials are firstly evaluated experimentally. Focusing on the comparison of experimental and simulation results, the DEM is used to probe the effects of polymer properties (permittivity, PM-fiber adhesion, fiber charge density) on the PM collection processes. It aims to give further insight into the mechanisms of the PM capture enhancements due to the dielectrophoretic effect and PM-fiber interaction.

2. Experimental

Four polymers of different permittivity, namely polyvinyl chloride (PVC), PAN, PC and polyethyleneimine (PEI) are used for filter preparations. Their relative permittivity values are 3.4, 3.26, 2.9 and 2.6, respectively. The four polymer powders are dissolved in the corresponding solvents to prepare the polymer solutions. All solutions are subjected to vigorous stirring for 6 h at 50 °C to ensure the complete dissolution of polymer powders. A commercially available electrospinning machine (SS-2535H) equipped with rotating substrate is used to create four nanofiber-based electret filters from the four solutions. By adjusting the electrospinning parameters, a set of electret filters, each with similar fiber diameter and fiber packing density are electrospun. The detailed electrospinning parameters are listed in Table 1.

The surface morphologies of the electrospun filters are characterized by a high solution field emission scanning electron microscope (FE-SEM) (LEO1530VP, Zeiss, Germany). As seen in Fig. 1, the nanofibers orient randomly to form a reticular structure, which would serve as a channel for the airflow, and also act as a particle collector by mechanical capture. The average fiber diameters, average pore sizes, and fiber packing densities of the four filters are shown in Fig. 2. The fiber size distribution is determined by measuring more than 50 fibers in a SEM image using an image analyzer (Adobe Photoshop CS2). And then the average fiber diameters are calculated based on the distribution approximations. The pore sizes are measured on a capillary flow porometer based on the principle of the liquid extrusion porosimetry technique [20]. The fiber packing densities of the filters α are obtained employing the following formula

$$\alpha = \frac{\rho_{\text{plm}} - \rho_{\text{fb}}}{\rho_{\text{fb}}} \times 100\% \tag{1}$$

where ρ_{plm} represents the density of polymer material, and ρ_{fb} signifies the density of nanofibrous filter.

During the electrospinning process, a high positive voltage is applied to the polymer solution. Vast charges are generated and they would be embedded into the filter. Thus the nanofibers are electrostatically charged. The initial potentials of the electret filters are measured by an electrostatic fieldmeter (FMX-003, SIMCO, JAPAN). Some physical parameters of the four electret filters are summarized in Table 2. Note that at least five measurements are taken at different positions of an area of $15 \times 15\,\text{cm}^2$, and the average values are recorded. As seen, the nanofibrous filters electrospun by different polymer solutions have similar morphology, similar average fiber diameter of about 265 nm, similar fiber packing density of about 1.37%, and similar thickness of about 10.50 μm.

To quantitatively characterize the electrostatic attraction in PM collection for electret filters, four mechanical filters are prepared from the corresponding electret filters by removing their charges. Kim et al. pointed out that, isopropanol (IPA) exposure could increase the charge mobility of electret and remove the charges effectively [21]. Thus, the electrospun electret filters are exposed in IPA aerosol for 2 h, and then are placed on the flat glass in a fume hood drying for 24 h. According to the previous experimental works [22], the fiber charges almost all disappear. The surface potentials of the mechanical filters are measured to be zero. Meanwhile, no observable morphological change via scanning electron microscopy imaging is found after solvent exposure. Since the dielectric constant is only influenced by molecular structure, chain structure of polymer and environmental conditions (eg. temperature, pressure, electric frequency et al.) [23], the dielectric constants of the mechanical filers keep the same as the corresponding electret filters.

An automatic fractional filtration tester (SX-L1060) is employed to evaluate the filtration efficiencies and pressure drops of the electrospun nanofibrous filters. As seen in Fig. 3, the compressed air is dried in an air dry condenser (HR 7.5AC RRT). The dry air is sucked into a high efficiency particulate air (HEPA) filter and is purified by it. To generate particles, another branch of particle-free compressed air is delivered to an atomizer to atomize the KCl solution (10 wt%). The particles firstly flow through a neutralizer, which brings the particles to be Boltzmann equilibrium. Then they pass through an electrostatic precipitator (ESP) in which the charged particles are removed. The voltage and the inlet airflow of the ESP are set to be 10.0 kV and 30 L/min to ensure completely removing of charged particles. The remaining neutral particles are blended with the dry-clean air in a mixer. A flowmeter controlled by an intelligent computer is used to regulate the air-particle flow entering into the test filter. The filter is fixed in a circular sample holder and the test area is $100\,\text{cm}^2$. The numbers of the KCl particles up and down the stream are measured by the condensation particle counters (Y09 5100, Suxin). A micro differential pressure gauge (UP 1 KPa, Duwei) is used to measure the pressure drop. Every reported experimental data is the average of three tests. During each test, the tester would automatically and continuously take the measurement five times, and the average value is given automatically.